

Thermal Analysis for Balloon-Borne Payloads

2016 Scientific Ballooning Technologies Workshop

Brian O'Connor (NASA/MSFC)

Introduction

The goal of these slides...

- Illustrate the complexities of the thermal environment for a balloon flight.
- Convince you why you should consider thermal environments in the initial development of a project.
- Provide some common thermal design strategies.
- Example of how to do quick hand calculations.
- Provide references for additional information.

Launch Sites Overview

- Determines:
 - Time of year (flight season),
 - latitude/longitude,
 - flight duration,
 - Earth IR,
 - Solar flux/albedo,
 - recovery temps, etc
- Six sites (considered for GHAPS – Gondola for High Altitude Planetary Science)
 - Fort Sumner, New Mexico
 - Palestine, Texas
 - Alice Spring, Australia
 - Kiruna, Sweden
 - McMurdo, Antarctica
 - Wanaka, New Zealand

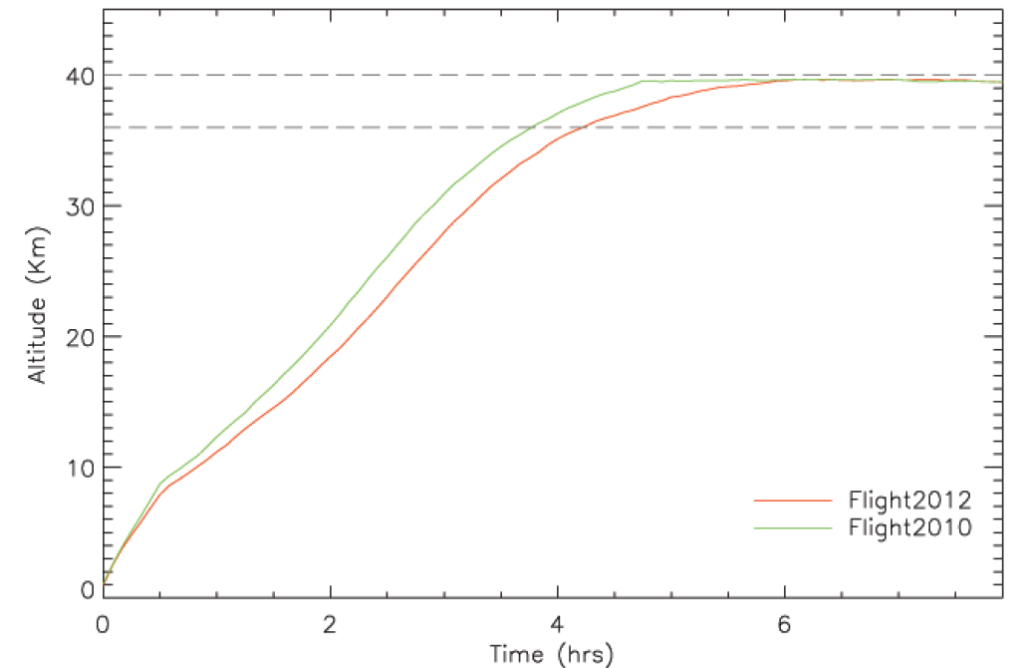
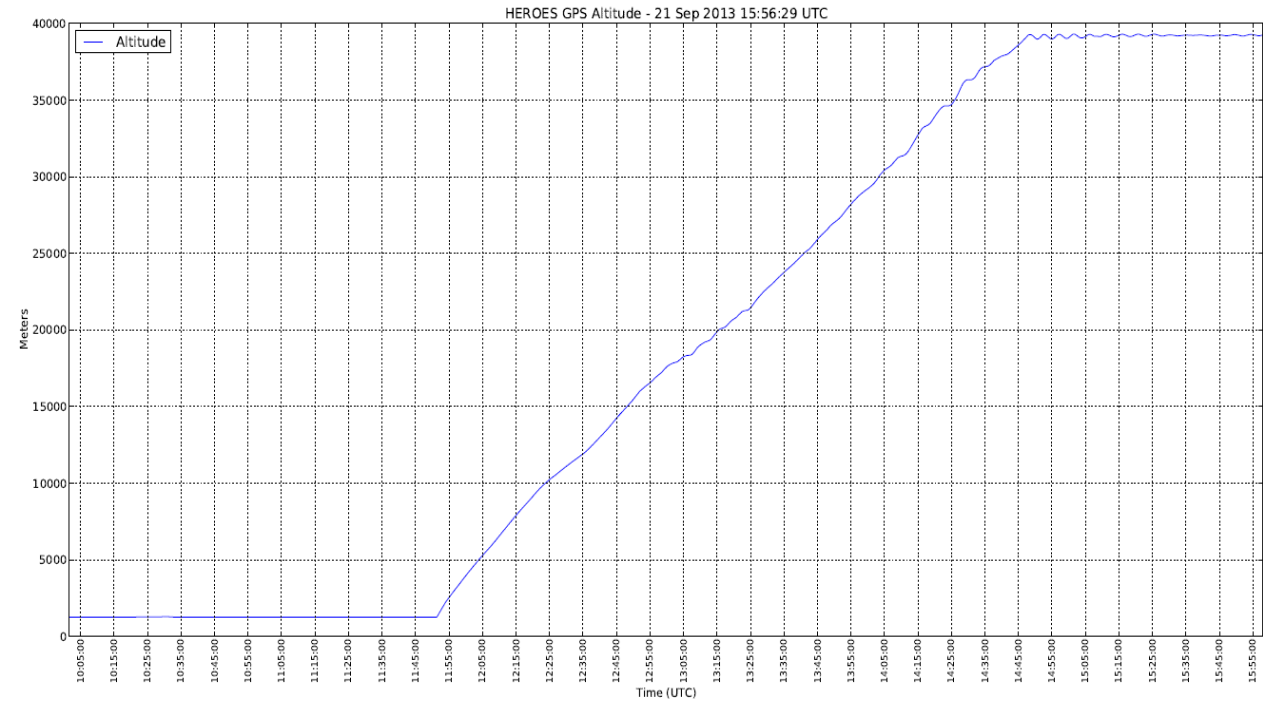
Launch Site Definitions

- Launch site matrix for GHAPS:

	Fort Sumner, NM	Palestine, TX	Alice Springs AUS	Kiruna, SWE	McMurdo, ANT	Wanaka, NZ
Flight Season	Aug - Oct	May - July	March - May	May - July	Dec - Jan	March - May
Lat/Long	34.47° N, 104.24° W	31.77° N, 95.71° W	23.80° S, 133.89° E	67.88° N, 21.12° E	77.85° S, 166.67° E	44.72° S, 169.24° E
Balloon Type	Zero Pressure	Zero Pressure	Zero Pressure	Zero / Super Pressure	Zero / Super Pressure	Super Pressure
Flight Duration	up to 24 hrs	up to 12 hrs	up to 36 hrs	up to 7 days	up to 50 days	up to 100 days
Average Recovery Temp	10 to 32 C 50 to 90F	21 to 38 C 70 to 100 F	10 to 21 C 50 to 70 F	-1 to 16 C 30 to 60 F	-18 to 4 C 0 to 40 F	4 to 21 C 40 to 70 F

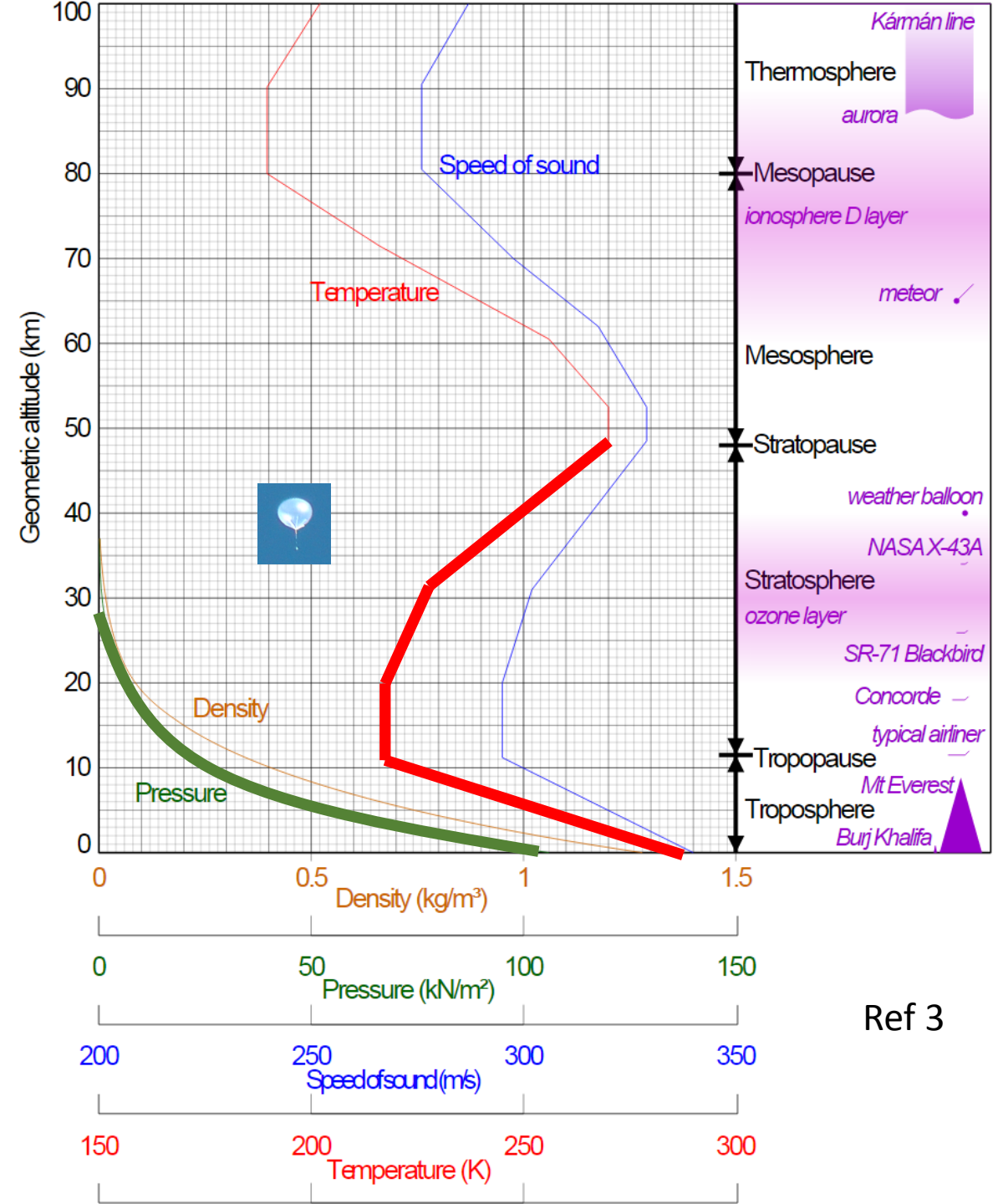
Ascent Overview

- Typical float altitude (Ref 1)
 - Zero pressure balloon: ~38km
 - 3 Torr
 - Super pressure balloon: 33-35km
 - 8 Torr
- Ascent Time
 - 2013 HEROES, Ft. Sumner: 3hrs
 - Avg velocity: ~ 11.3 km/hr
 - 2010/2012 BLASTPol, Antarctica: ~4-5hrs (Ref 2)
 - Avg velocity: ~7.4-7.8 km/hr



Ascent Definitions

- Air temperature varies considerably during ascent
- Lowest air temperature occurs at tropopause ($\sim -70^{\circ}\text{C}$)
 - For some components this may be the worst case cold that you'll need to size your heaters for.
- Once at float altitude
 - Air temperature will have increased.
 - However, the pressure is so low that an object's temperature is more determined by its radiative heat transfer
 - Reduces the ability to dissipate heat



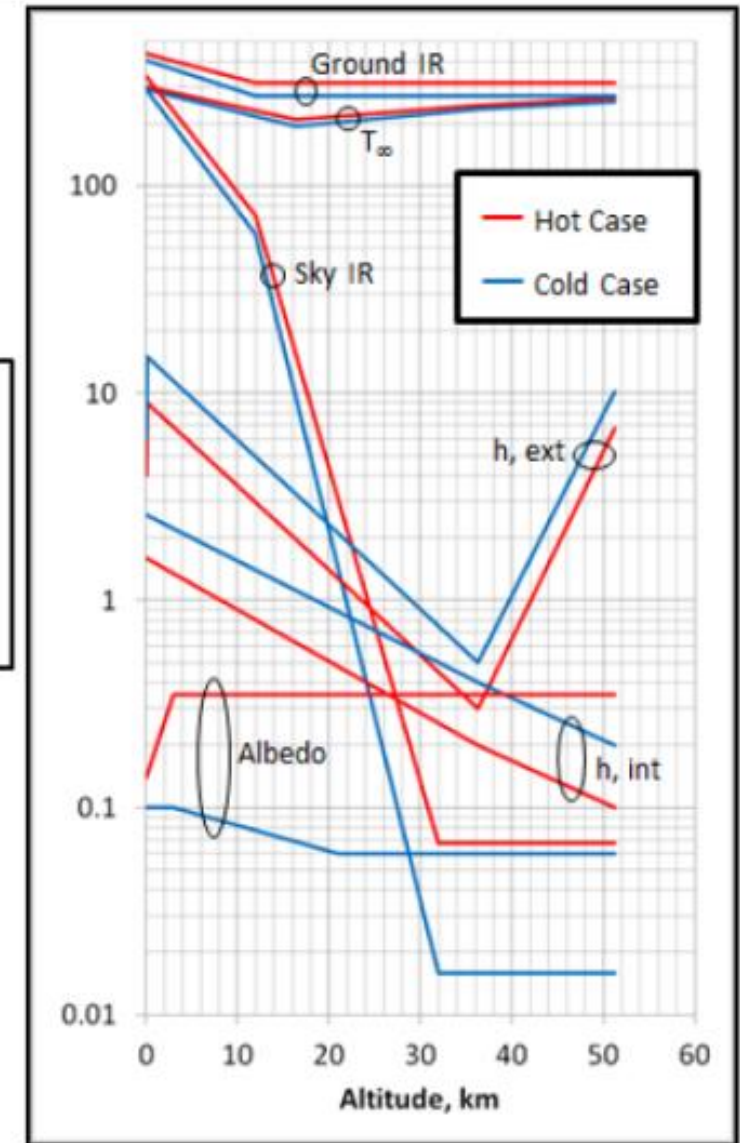
Ref 3

Ascent Definitions

- Thermal variables that vary during ascent:
 - Air temp
 - Convection (ascent speed, air pressure)
 - Ground/Sky IR
 - Solar flux
 - Albedo
- Picture to the right shows a good example of creating hot and cold bounding environments for ascent
 - From JPL's Low Density Supersonic Decelerator (LDSD) project (Ref 4)

Ref 4

Vertical Axis Units:
Ground IR: W/m^2
Sky IR: W/m^2
 T_∞ : K
 h , ext, int: $\text{W/m}^2\text{K}$
Albedo: none



Ascent Summary

- Very transient, with many environmental variables changing.
- May be your worst case cold for sizing heaters.
 - So don't neglect it
- Sets your initial conditions for float analysis.
 - Important for a thermally heavy object and a short flight duration (e.g. a primary mirror)
- Condensation may occur, usually evaporates by the time of float, but needs to be considered if it's a risk during ascent.

Float Overview

- Temperatures mainly driven by radiative properties
 - Environment and surface coating
 - Plate painted white = 26°C
 - Plate polished aluminum = 236°C
 - See example of a simple calculation slide
- Radiation much less effective at cooling, thermally heavy objects will take much longer to cool
 - When it may take $\sim 1\text{hr}$ to cool a primary mirror down with air convection on the ground, may take days at float.



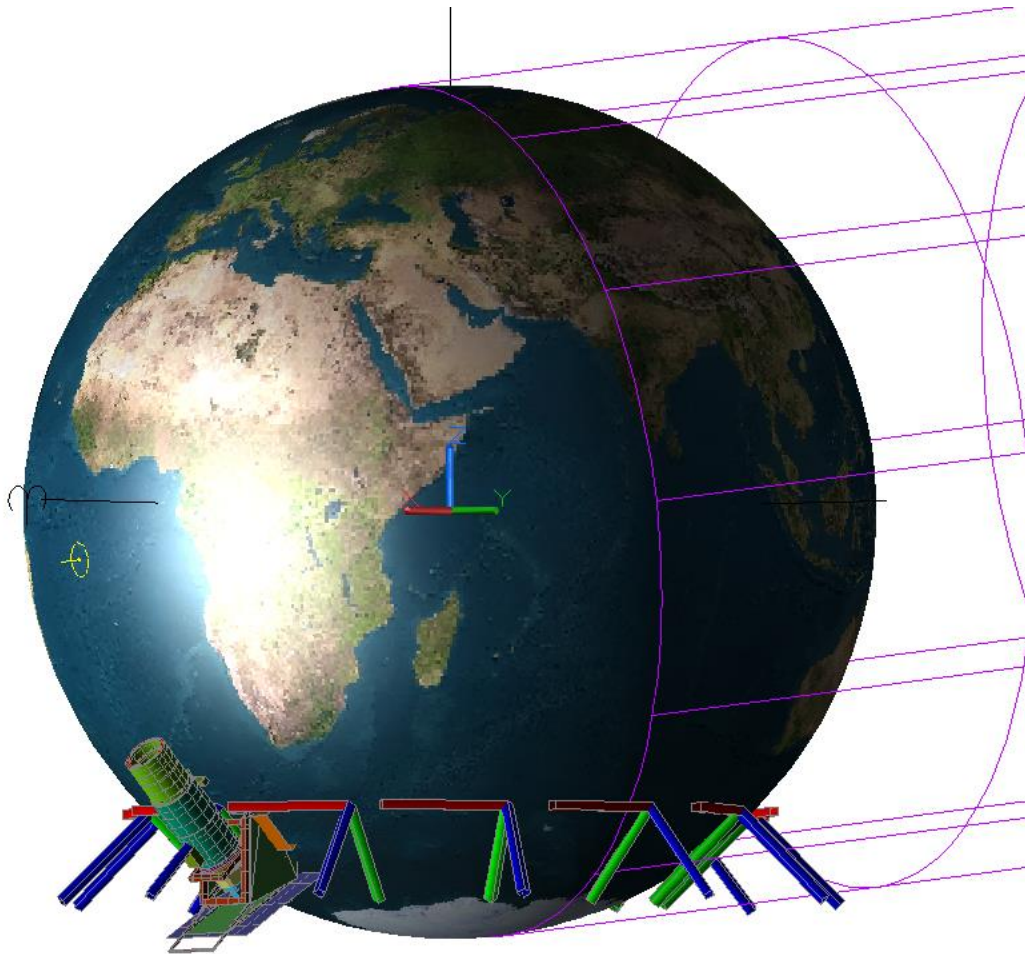
Float Definitions

- For a launch location need to define:
 - Date and latitude
 - If mission is long duration then a min/max latitude
 - Solar flux
 - Determined by date of year
 - Albedo, Earth flux
 - Generally high albedo occurs same time as a low Earth flux (e.g. over clouds, ice)
 - Vice versa (e.g. over hot desert)
- Two cases for each site: hot and cold
- Then add in pointing
 - Defined science con-ops help out a lot
 - If con-ops aren't defined then time will be spent running parametric to find worst case pointing.
- Including thermal analysis and parametrics early in the project will help constrain the impact of environments to simplify design, cost, and schedule by defining initial science requirements.

Example environment for New Zealand (Info from CSBF/NMSU)

- **Hot Case:**
 - Date March 1st (beginning of launch window)
 - Length of night: ~9.5hrs
 - Latitude: 44.7°S
 - Solar Flux: 1368 W/m²
 - Albedo/Earth IR: 10.68%, 288.3 W/m²
- **Cold Case:**
 - Date June 22nd (winter solstice in southern hemisphere)
 - Length of night: ~17 hrs
 - Latitude: 65°S (assumes balloon drifts south)
 - Solar Flux: 1304 W/m²
 - Albedo/Earth IR: 63.48%, 176.6 W/m²
- Note if object is more sensitive to solar heating than earth IR, may need to switch albedo/earth IR from the two cases.
- Depending on operating temperature, may want to add use vacuum for hot case, and convection for the cold case.

Example Orbit (New Zealand)

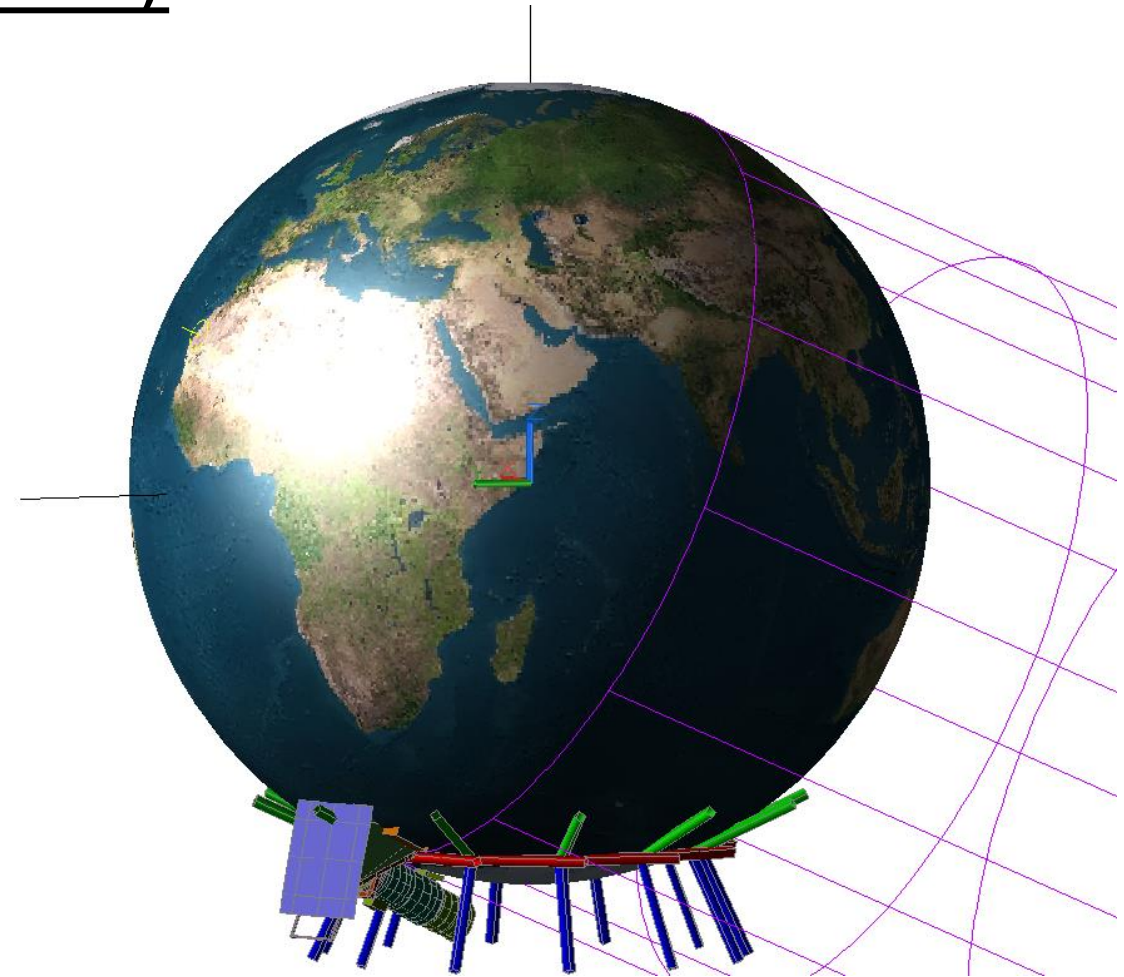


Hot

Beginning of flight: March 1st

44.7°S latitude

Length of night ~9hrs



Cold

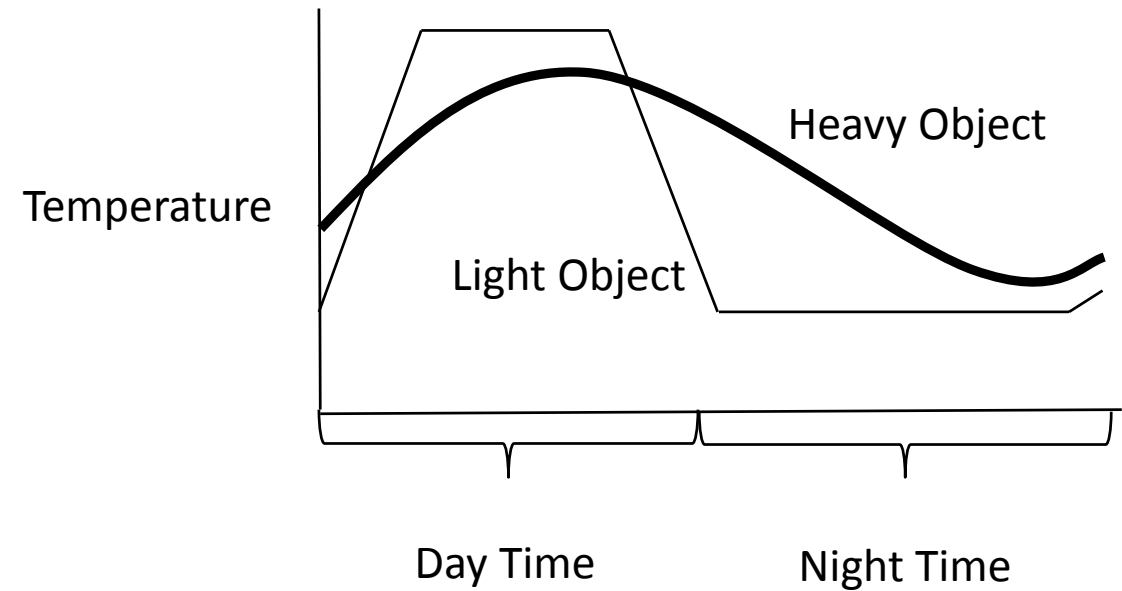
Winter solstice: June 22nd

65°S latitude

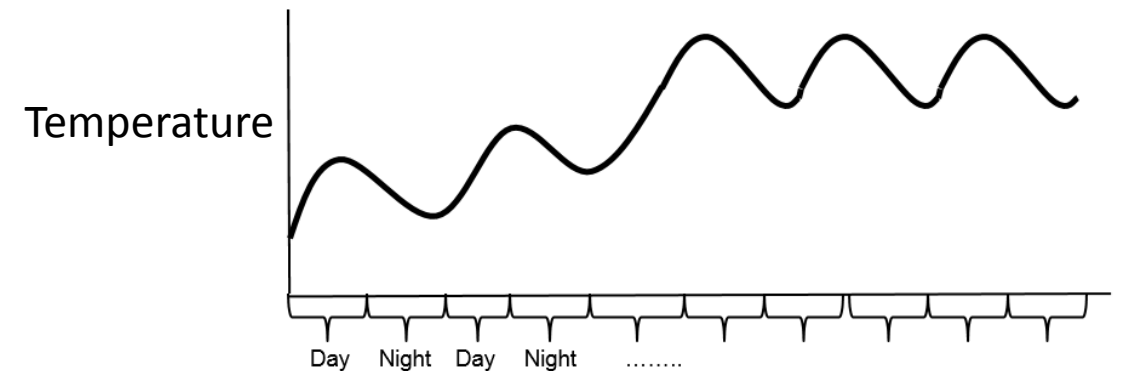
Length of night ~17hrs

Thermal Stability

- A thermally light object will reach a steady state temperature quickly
 - Day/night, and pointing
 - E.g. a thin flat plate
- A thermally heavy object may never reach steady state, it could reach a transient equilibrium
 - However if environment changes then it'll have to reach a new equilibrium
- If thermal stability is important
 - Lighten the object
 - Use active thermal control (e.g. heaters) to maintain the object at near constant temperature



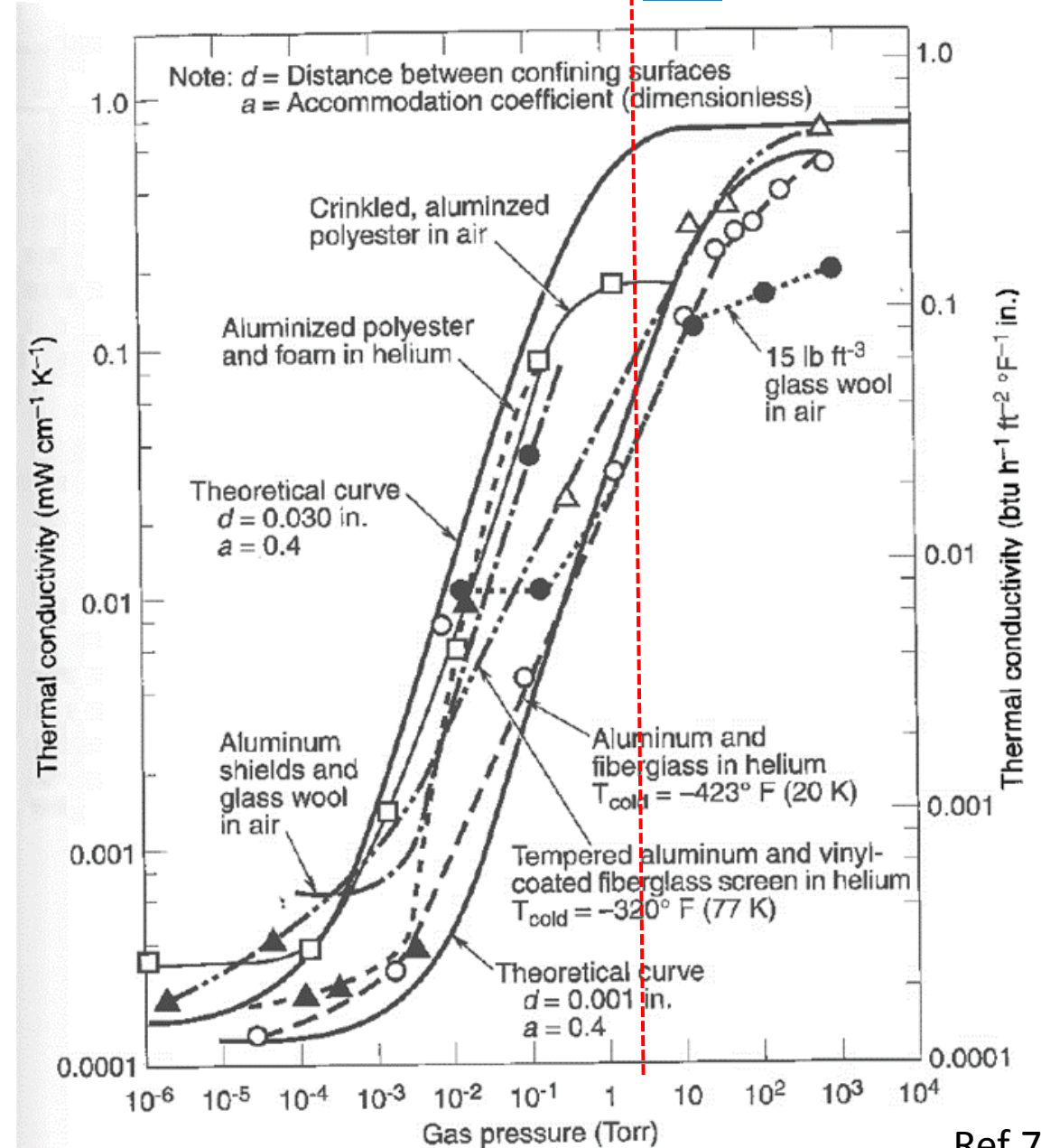
Heavy Object Reaching a Transient Equilibrium



Common Implementations

- Surface coatings
 - Typically want a solar absorptivity (α) / IR emissivity (ϵ) < 1
 - White paint
 - Sherwin Williams A6W40: $\alpha/\epsilon = 0.29$
 - Metal coated film (e.g. aluminum, silver) (e.g. Kapton, mylar)
 - Acts as a second surface mirror
 - Can be bought with an adhesive back.
 - Silver Teflon (10 mil): $\alpha/\epsilon = 0.1$
- Insulation
 - Typical spacecraft MLI isn't effective for balloons.
 - CSBF recommends (Ref 6):
 - Ethafoam, XPS (extruded polystyrene), Melamine

Typical Pressure Environment



Example of Quick Hand Calculation

- For a rough ballpark type of calculation, assume:
 - Single object floating in space
 - Half area sees the sun, other half sees the earth
 - Radiation only heat transfer
 - Steady state
 - Results in a single unknown
- Example, computer having 0.5m² area, with 50W dissipation:
 - Painted white ($\alpha/\epsilon = 0.24/0.9$)
 - Using New Zealand fluxes listed earlier
 - Worst case hot = 26°C
 - Worst case cold = -30°C
 - If used alodine ($\alpha/\epsilon = 0.45/0.12$)
 - Worst case hot = 236°C

$$Q_{stored} = Q_{in} - Q_{out} + Q_{generated}$$

$$Q_{in} = Q_{solar} + Q_{IR} + Q_{albedo}$$

$$Q_{in} = \alpha \cdot A_{sun} \cdot q_{solar} + \epsilon \cdot A_{earth} \cdot q_{earth} + \alpha \cdot A_{earth} \cdot albedo \cdot q_{sun}$$

$$Q_{out} = \sigma \cdot \epsilon \cdot A \cdot T^4$$

(assumes seeing no other temperature source)

(σ : Stephan-Boltzman constant)

$$Q_{stored} = 0$$

Example Flight Temperatures

2013 HEROES Flight in Ft. Sumner (~25hrs)



Temperatures on next slide are from the rear optical bench

HEROES: High Energy Replicated Optics to Explore the Sun

BLASTPol Flight in Antarctica (~210hrs) (Ref 5)

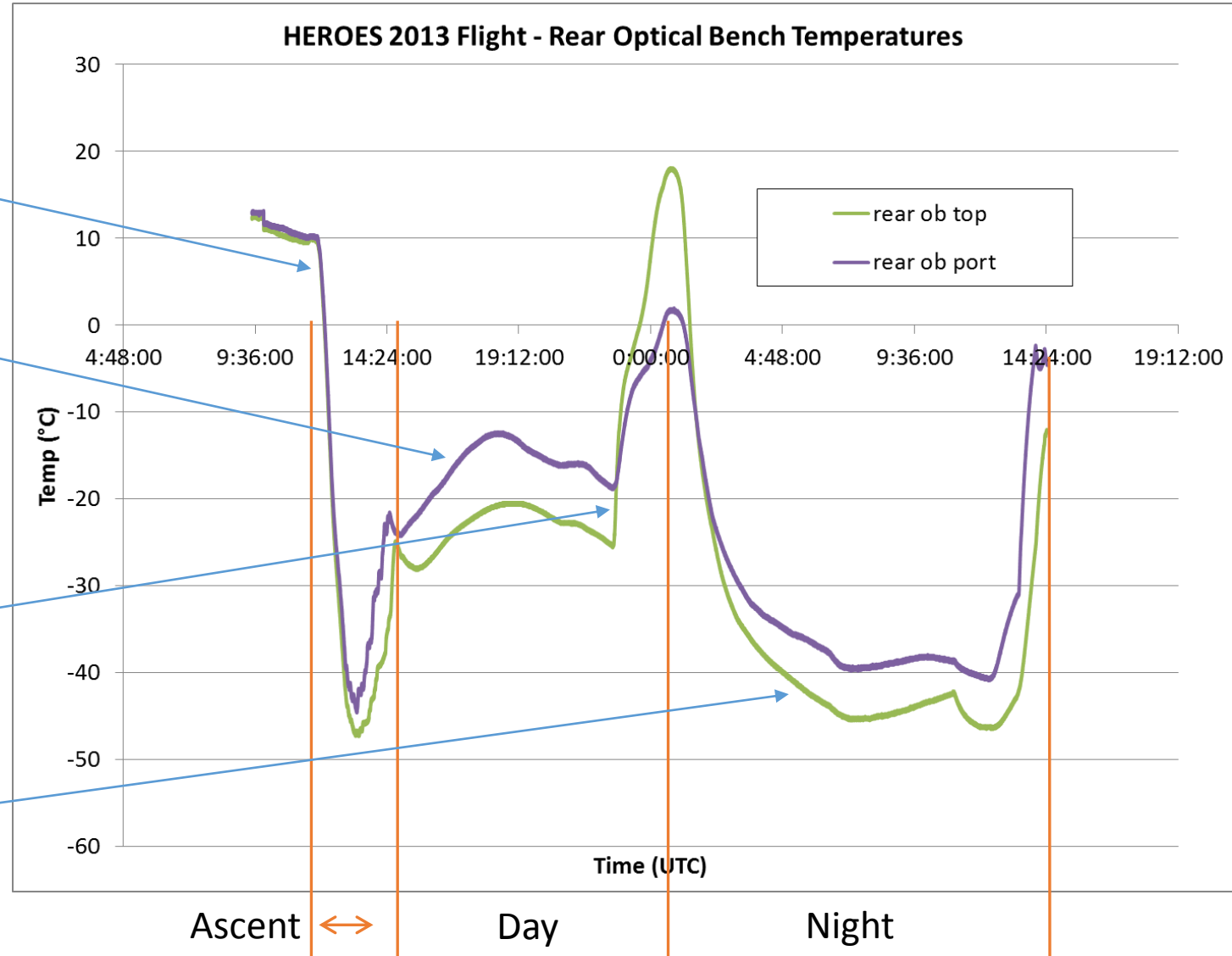


Temperatures from primary mirror (Ref 2)

BLAST-Pol: Balloon-borne Large-Aperture Submillimeter Telescope for Polarimetry

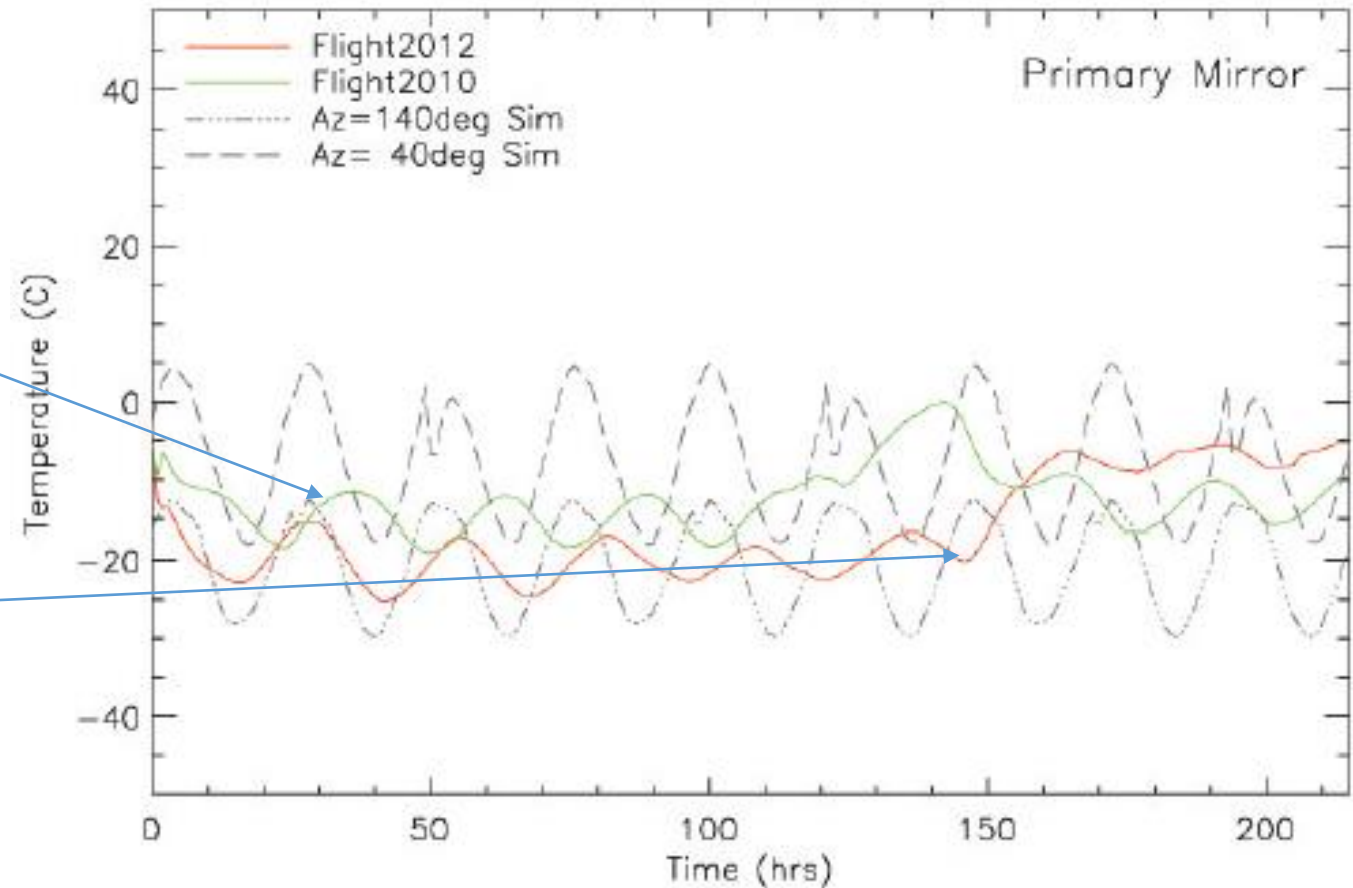
HEROES

- Flight is ~25hrs, Ft. Sumner
- Ascent: temperatures drop very quickly then warm up by float
- While pointed at the sun the temperatures are tracking with environmental changes
 - Reaches max at noon then starts to cool down
- Changing pointing causes a new steady state point
- Transitioning to night causes a new steady state point
 - Telescope doesn't change in pointing so temperatures are pretty stable



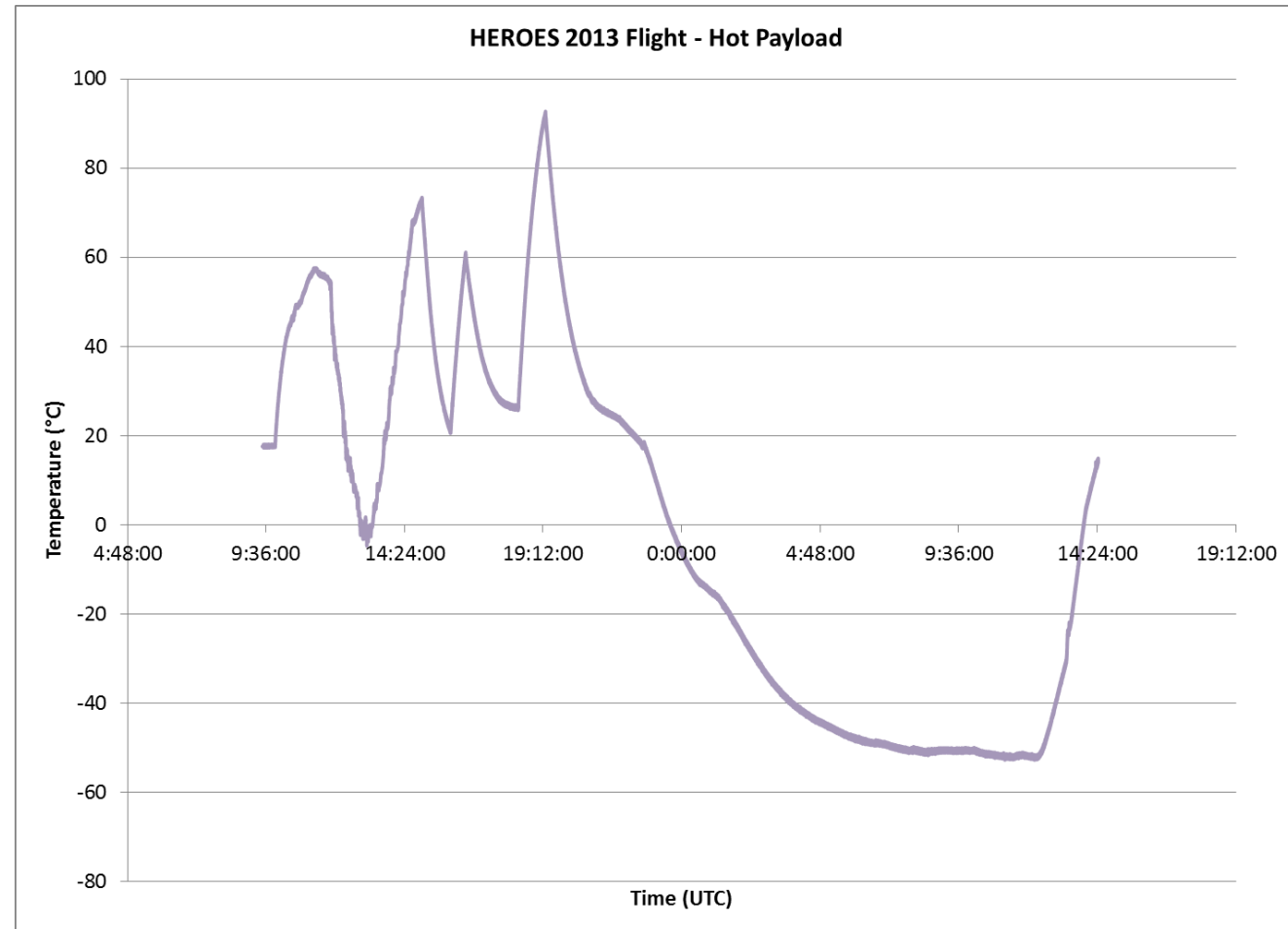
BLASTPol (Ref 2)

- Flight is ~210hrs
- Antarctica
- Mirror is around a transient equilibrium
- Appears something occurred in environment that caused a temperature shift



Example of Not Including Thermal

- Temperature plot of someone who caught a ride on the HEROES flight
 - Appears to not have really considered thermal
- What I think went on in their heads:
 - “It’s cold up there, the air temperature is -40°C , our payload will stay cool.”



Balloon Thermal Best Practices

From Scott Cannon at New Mexico State University:

- Thermal needs to be considered from the beginning of the design, not as an afterthought.
- Mechanical models generated by the science groups need to be up to date and representative of the actual flight hardware.
- New/different surface finishes require optical property testing (α, ϵ).
- All power sources need to be identified with representative cycles.
- Temperature limits must be provided, unpadded and as wide as possible (testing-derived).
- Thermal needs to be in the loop for all potential changes no matter how small.

References

1. Eliot Young, et. al. "Passive Thermal Control of Balloon-Borne Telescopes". 2015 IEEE Aerospace Conference
2. J. D. Soler, et. al. "Thermal Design and performance of the balloon-borne large aperture submillimeter telescope for polarimetry BLASTPol", 2014, Proc. Of SPIE Vol 9145 914534-1
3. "Comparison of the 1962 US Standard Atmosphere graph of geometric altitude against air density, pressure, the speed of sound and temperature with approximate altitudes of various objects."
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4. A.J. Mastropietro, et. al. "Thermal Design and Analysis of the Supersonic Flight Dynamics Test Vehicle for the Low Density Supersonic Decelerator Project", AIAA ICES Conference 2013
5. http://science.nasa.gov/media/medialibrary/2013/04/22/secure-JONES-Jones_APS_041613_Final.pdf
6. **CSBF "Structural Requirements and Recommendations for Balloon Gondola Design". OM-220-10-H, April 23, 2013 (www.csbf.nasa.gov)**
7. David Gilmore, "Spacecraft Thermal Control Handbook, Volume 1". The Aerospace Corporation 2002

Thanks

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